Relative Positioning of Mobile Robots Using Ultrasounds

Jonathan Bisson[1], François Michaud[1], Dominic Létourneau[1]

[1] *Université de Sherbrooke, Sherbrooke (Québec Canada), laborius@gel.usherb.ca*

Abstract

For robots to move in formation or to make them cooperate for distributed sensing of an area, they need to be able to determine their positions relative to each other. Instead of using an absolute positioning approach, we have developed a relative positioning device that allows to perceive the distance and the angle of other nearby devices. The system is based on time-of-flight evaluation of ultrasonic waves and a RF communication link. The approach is validated using two Pioneer 2 robots in a leader-follower configuration.

1 Introduction

To be able to coordinate their actions in a group, mobile robots need to determine the positions of others in the environment. One way of doing so is to use an absolute positioning system like GPS (which is not quite precise enough for small and medium size robots, and cannot work indoors), a map or ultrasonic beacons [2, 3, 4]. A robot determines its position in relation to beacons, and communicates its position to others using a radio link. By sharing a common reference frame, robots can determine easily where the others are in relation to itself just by comparing their positions with its own. Even if they do not sense their presence directly, they can infer this way the presence of others nearby. For such approaches to work, engineering of the environment (to place the beacons or to map the environment) is required, and this is part of the a priori knowledge the robots must have to operate properly.

However in real life settings (which are very opened and dynamic) or environments that cannot be altered, it may not be possible to modify or to model the environment this way. It may be more appropriate for a robot to be able to directly perceive the position (in distance and angle) of others in its surroundings. Humans do this all of the time using vision, and mobile robots can use it too [1, 6, 7, 8]. For instance, vision has been shown to improve the localization capabilities based on map [5]. However, vision is an expensive sensor (in money and processing time, even more so with omnidirectional cameras), and currently mostly colors are used to identify robots. Such method is affected by luminosity and the presence of objects of the same color(s) in the operating environment.

To overcome these limitations, we have developed a portable ultrasonic positioning device that can be used by robots to detect the distances and the angles in relation to each other. The device consists of one transmitter, three receivers and one RF communication link. The detection approach is based on time-of-flight evaluation of ultrasonic waves. After describing the approach, the paper presents the implementation of the device and the results obtained. Validation is done using one Pioneer 2 robot following another using the device.

2 Relative Positioning Using Ultrasound

The purpose of the relative positioning devices is to put them on mobile robots so that they can determine the distance and the angle of the others in relation to itself. No common reference frame exists: each robot determines the position of the others in relation to its own.

Using time-of-flight evalutation of ultrasonic waves [3, 4, 9], the common approach is to mount a transmitter on a robot and to place several receivers at prespecified locations with respect to a reference frame. But instead of placing these receivers in the environment and use a fixed reference frame, we mount the receivers on a mobile robot so that the reference frame is the robot itself. To lower the number of sensors required, the device give only the 2-D location (distance and angle). To have a 3-D location (i.e., height), one sensor must be added.

To be more specific, each positioning device comes equipped with one transmitter, three receivers and a RF communication link. The positions of the receivers in relation to the mobile robot are known. The device determines the position of a transmitter based on distance measurements to the receivers. The transmitter on one device generates an ultrasonic wave, and at the same time signals this emis-

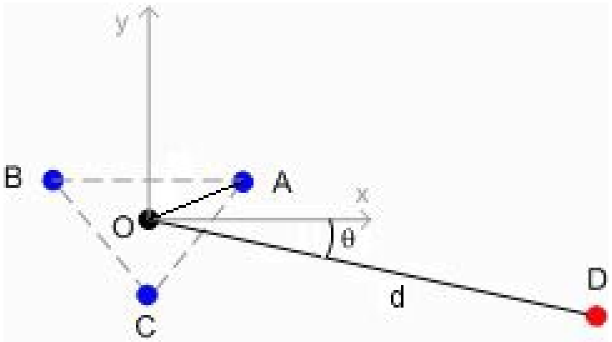

Figure 1: *Three fixed receivers (A, B, C) and one transmitter (D).*

sion to other devices using the RF communication link. Since RF waves travel at the speed of light (3×10^8 m/s), the signal is detected by the receiving devices almost instantaneously. Ultrasonic waves travel at the speed of sound v (in m/s), which is slow compare to the speed of light. The speed of sound is affected by the temperature T (in Celcius). In our experimentations, we supposed a constant temperature so we use a constant as the speed of sound. In environnement where this speed can change, a temperature sensor can be used to adjust the speed of sound in real time.

At 20° Celcius, the v is equal to 343 m/s. Using the time delay TOF detected by one receiver, the distance d between the transmitter j and the receiver i can be found by multiplying it with the speed of sound, as expressed by equation 1. Multpath propagation of ultrasonic waves (caused by reflections) is not an issue here, since only the first detection (coming directly from the transmitter) is relevant. Accuracy is the biggest challenge with the device. Intuitively, increased accuracy can be obtained when the receivers are far away from each other, because the delay measurements have a greater dynamic range. Putting the receivers over the same mobile robots may then become an issue.

$$d_{ij} = TOF_{ij} \cdot v(T) = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2} \quad (1)$$

$$\begin{bmatrix} 2(x_B - x_A) & 2(y_B - y_A) \\ 2(x_C - x_A) & 2(y_C - y_A) \end{bmatrix} \begin{bmatrix} x_D \\ y_D \end{bmatrix} = \begin{bmatrix} d_{AD}^2 - d_{BD}^2 + x_B^2 - x_A^2 + y_B^2 - y_A^2 \\ d_{AD}^2 - d_{CD}^2 + x_C^2 - x_A^2 + y_C^2 - y_A^2 \end{bmatrix} \quad (2)$$

As shown by Figure 1, using one transmitter (D) and three receivers (A, B and C) with known positions in relation to the origin (O), the distances between the receivers and the transmitter can be derived with Equation 1. Using this equation to express d_{AD}^2, d_{BD}^2 and d_{CD}^2, the (x_D, y_D) coordinates of the transmitter can be expressed by Equation 2.

Before implementing the positioning device, we simulated it by placing the three receivers at a radius $r = 100$ mm and $\theta = 30°$, 150° and 270° around the origin. We evaluated in the simulations two types of errors that could affect the accuracy of the device: absolute error which is common to all the receivers, and relative errors which are different for each receivers. The absolute error can be introduced by the attenuation of the waveform, the processing required for the RF communication link or an error on the speed of sound used by the system. The relative errors can be caused by the small differences of the components of the receivers or the presence of objects surrounding the receivers. Simulations have shown that the resulting coordinates (x_D, y_D) are very sensitive to noise on the measurements of TOF made by the receivers. Deriving both the distance d and the angle θ from (x_D, y_D) leads to a significant error on d, but gives a good precision on θ. Thus, θ is derived from (x_D, y_D) and d is derive from the average over the three TOF, which give much better precision. The simulations have shown that d is affected by both types of errors while θ is mainly affected by relative errors. With absolute and relative errors set to approximate the behavior of the real device, the absolute mean error is 10.3 mm on d and 2.2° on θ over an area of 20 m $\times$ 20 m. Distance measurements are also influenced by the difference in height between the transmitter and the receivers (a phenomenon that increases as the positioning devices are close to each other), but this can be corrected if this difference in height is constant and known. We have also simulated the influence of r (from 50 mm to 300 mm) on the performance of the device. We set the lower limit is set to 50 mm because in practice, it is hard to bring the receivers closer. We observed that r influenced mostly the angle measurements. In the worst case ($r = 50$ mm), the absolute mean error is around 10 mm and 5°. The accuracy on θ increases rapidly when receivers are distant: at 300 mm, the absolute mean error is around 10.86 mm and 0.74°. The small increase on the distance error is caused by taking the average of TOF from the three receivers to derive d: this approximation is valid only when the receivers are close to each other (i.e., when r is small).

3 Implementation and Results

First, two choices must be made for the design of the device. One is for making the device omnidirectional.

We decided to use a cone that reflects all incoming and outgoing ultrasonic waves toward an ultrasonic transducer placed at the bottom [2, 9], as shown in Figure 2. The cone we used are made using plaster of Paris. We also tested the device with an aluminum cone, and the results obtained were similar.

Figure 2: *Reflector cone on top of a transducer, making it omnidirectional.*

The second choice is the type of ultrasonic transducers to use. Electrostatic transducers operate on larger frequency band and range, and are more sensitive than piezoelectric transducers. Piezoelectric transducers are less expensive, smaller and require lower voltage levels, and so we chose to use them in our first prototype. To select the operating frequency of the transducers, using a higher frequency tends to increase the accuracy of the measures, but with a greater diminution of the perceptual range. Since the objective with this first prototype of the device is to evaluate the feasibility of the concept, we decided to use piezoelectric transducers at 40 kHz for cost and availability reasons.

Figure 3 represents the system without the transmitter. The transmitter would normally be placed over the controller, higher than the receivers to avoid interfering with incoming ultrasonic waves. The RF communication link is a BIM2 transmitter/receiver at 433.92 MHz from Radiometrix. The controller used is a PIC16F877 at 20 MHz (5 MIPS). The microcontroller uses an internal counter to evaluate the time-of-flight of the ultrasonic pulse, giving it a maximum resolution of 4.2 us and a maximum value of 26.2 ms (resolution of 1.44 mm and maximum value of$d$ = 9 m range at 343 m/s). The sensing rate of the receivers depends on the operating range desired for the device: assuming that the power of the ultrasonic wave emitted is set to the minimum power required to cover the desired range, the time between two emissions must be at least four time the time required for the ultrasonic wave to travel this distance, to make sure that the wave is completely attenuated when the next transmission begins. For instance, since it takes 26.2 ms for an ultrasonic wave to travel 9 m, the minimum time between two emissions would be 104.8 ms. The experimentations have shown that this rule is sufficient but may be optimized to increase the maximum data rate of the ultrasonic device.

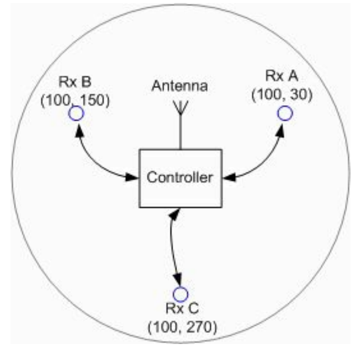

Figure 3: *Disposition of the receivers Rx (A, B, C) and the controller with its RF link.*

Before testing however, it is necessary to calibrate the receivers. The process consists of determining the value of a constant to substract to the TOF calculated by each receiver. This constant allows to compensate for errors caused by the transmission delay via the RF communication link (the device examines a checksum and verifies the message received, which requires some processing time), the distance traveled by the ultrasonic wave from the cone to the transducer, and the difference between the response time of the ultrasonic transducers. The procedure is simple: it requires taking measurements at known distances and using Equation 1 to find out the difference between the real TOF and the measured TOF for each receiver. We took several measurements on the entire operating range to find the optimal calibration that can take into account the dissymmetrical response of the device. A least-squares method is used to combine all the calibration results. These adjustments are important since the accuracy of the angle measurements is very sensitive to an offset between the receivers. The calibration constants are set around 88 us, which correspond to 30 mm at 343 m/s.

Figure 4 shows the experimental setup. The first set of tests consists of placing one transmitter at the vertical, and changing d and θ defined in Figure 1. Measurements were made from $d = 500$ mm to 8100 mm every 200 mm, rotating the device from 0° to 360° with 10° increments. Twenty measures were made at each position. The TOF_{ij} measures from the receivers are sent to a Pentium 233 MHz computer for processing. The calculations take about 130 us without any code optimization. The error introduced by positioning manually the receivers is evaluated at less than ±75 mm and ±3°. Figure 5 illustrates the errors of the position measured by the device in relation to the distance between the transmitter and the over 360°. The distance error varies from -17 mm

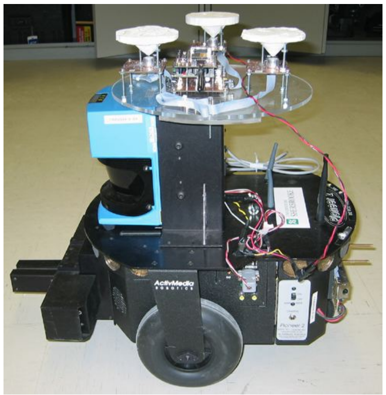

Figure 4: Experimental setup.

to 28 mm with an absolute average of 3.75 mm and a standard deviation of 3.35 mm. The angle error varies from -17° and 8° with an absolute average of 1.84° and a standard deviation of 1.79°. The increase in standard deviation over the distance is caused by the attenuation of the ultrasonic wave. Figure 6 illustrates the errors of the position measured by the device in relation to the angle for distances from 500 mm to 8100 mm. Theoretically, the device should be symmetrical, but the results confirm the presence of dissymmetry especially between 220° and 320°. This is probably caused by difference between the cones or obstruction created by the controller.

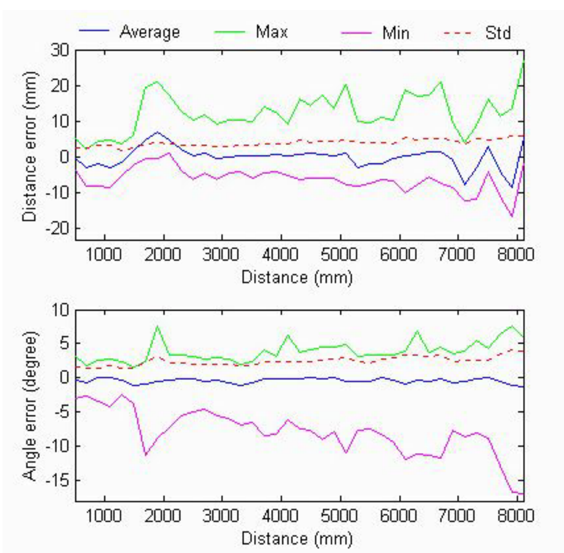

Figure 5: Errors in distance (top) and angle (bottom) from 500 mm to 8100 mm over 360°.

Table 1 compares results for two r, the distance between the receivers and the origin. These results confirms that the accuracy on the angle is better when

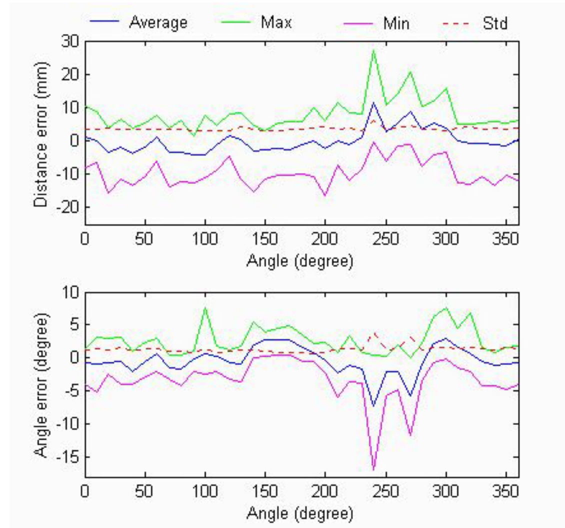

Figure 6: Errors in distance (top) and angle (bottom) from 0° to 360°, over 500 mm to 8100 mm.

Table 1: Errors of the ultrasonic device for different distances between the receivers and the origin

r mm	Abs. Avr. (mm,°)	Abs. Max (mm,°)	Std (Abs) (mm,°)
100	(3.75, 1.84)	(27.18, 16.93)	(3.35, 1.79)
150	(3.5, 1.22)	(25.15, 10.487)	(3.0, 1.23)

r increases. Unlike the simulations, the accuracy on distance is also better when the distance between the receivers is larger. This is probably due to the fact that the cones of the receivers cause more obstruction when the receivers are placed close to each other.

The second set of tests consists of using the device to actually make a mobile robot followe another, to see how the device performs on a moving platform. To approximate the position of the leading robot and to validate the measurements made by the device, we used a SICK laser range finder. The transmitter is installed on the leading robot, on top of a triangular base used by the laser to discriminate the robot. This position is the one used to evaluate the distance between the two robots by the laser range finder. The distance r between receivers was set to 100 mm. The device is placed over the laser ranger finder, with the origin 120 mm from the focal point of the laser. The measures made by the laser were adjusted accordingly. Figure 7 shows a top view of the robots and a photo of the experimental setup.

The robot equipped with the ultrasonic device is set to follow the leading robot at a specified distance and angle. Note that the angles specified are limited by the ability of the laser to always detect the triangle as the closest object. Figure 8 shows the differences

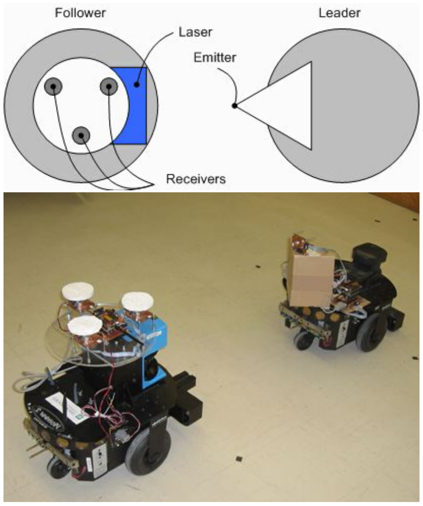

Figure 7: *Experimental setup using two robots.*

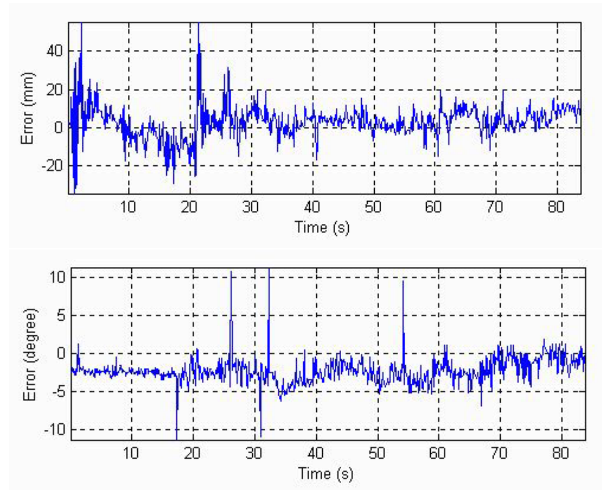

Figure 8: *Differences between the measurements made by the ultrasonic device and the laser range finder.*

between the measurements made by the ultrasonic device and the laser range finder during one trial, as the follower moves to follow the leading robot at 750 mm and 0°. The difference in distance varies from -30 to 50 mm, with an average of ±6.68 mm. The errors are larger in the first 30 sec of the trial because the leader changed speed at time 1 sec and time 21 sec. Since the ultrasonic positioning device returns data to the onboard computer about four times faster than the laser, this introduces errors between the two devices. This is especially true when the leading robot changes speed, creating a rapid change in the distance between the two robots and making the following robot readjust its speed while positioning itself in relation to the leading robot. The difference in angle is stable during the trial, except five times where the ultrasonic device made ponctual errors. Such errors can easily be eliminated assuming that the transmitter cannot change position instantaneously by more than 10°.

Table 2 presents the errors observed between the measurements made by the ultrasonic device and the laser range finder for different desired leader-follower configurations. These errors are calculated over all experimentals data for each configuration. The average absolute errors are less than 1% on d and θ, which confirms that the device is very efficient for relative localisation of mobile robots.

4 Related Work

Figueroa and Mahajan [3, 4] presented one of the first approaches that used ultrasounds for robot localization. The robot is equipped with one transmitter, and the receivers are placed on an inertial frame of reference for global positioning. Their approach required one more receivers to ours (five instead of four for 3-D and four instead of three for 2-D), allowing the system to determine the speed of sound. No details are given on synchronization between the transmitter and the receivers or on the orientation and the beam angle of the transmitter and receivers. The error is less than 2.54 mm over approximately 6 m^3, and it does not seem to have been actually used on mobile robots [3]. Wu and Tsai [10] also use ultrasounds localization, but with three transmitters in the environnement and two receivers on a mobile robot. This approach, which uses the transmitters placed higher than the receivers, can determine the 3-D position and the orientation of the robot assuming that the transmitters are positioned at (0,0,0), (a,0,0) and (0,a,0). Again, no details are given on the orientation and on the beam angle of the transmitters and the receivers (we assume that the transmitters are pointing down toward the receivers). Only two test positions are reported in the paper, placing the receivers at 150 cm and 190 cm right below the transmitters, making it hard to compare with our approach. The average accuracy is around 6 mm on the position. Our system has been characterized and tested in much more diverse test conditions, and have shown good precision and results.

One implementation of ultrasonic localization devices is with the Millibots [9]. Ultrasounds are used to determine the distances between robots. An aluminum cone is used on top of the tranceiver, and like our device the device simultaneously emits a RF pulse and an ultrasonic pulse. But each robot is equipped with only one transducer, and so it can

Table 2: *Errors of the ultrasonic device for different parameters*

(r,θ) $(mm,^\circ)$	Abs. Avr. $(mm,^\circ)$	Abs. Max $(mm,^\circ)$	Std (Abs) $(mm,^\circ)$
(750, 0)	(6.68, 2.19)	(55.45, 11.72)	(6.4, 1.28)
(1500, 0)	(6.67, 2.2)	(65.47, 11.45)	(6.93, 1.19)
(2000, 0)	(7.8, 2.14)	(80.02, 11.36)	(10.1, 1.27)
(2500, 0)	(9.02, 1.35)	(69.89, 10.4)	(10.01, 1.23)
(1500,30)	(5.92, 2.09)	(80.52, 14.09)	(6.33, 1.82)
(1500,20)	(4.72, 1.7)	(41.74, 13.52)	(4.28, 1.62)
(1500,10)	(4.93, 2.26)	(41.17, 12.87)	(4.85, 1.41)
(1500, −10)	(8.54, 1.95)	(69.43, 11.39)	(8.65, 1.34)
(1500, −20)	(7.4, 1.91)	(43.0, 12.42)	(6.73, 1.52)
(1500, −30)	(7.48, 1.41)	(42.1, 12.02)	(6.17, 1.43)

only determine the distance between one robot to another. To determine their relative angles, three Millibots are used as fixed beacons, and one is set as the reference point. The "beacon" robots transmit one at a time, and all the surrounding robots evaluate their distances from these beacons simultaneously. The "beacon" robots change over time following a "leap-frogging" fashion, and an error on the position of one beacon will affect the positioning of all of the others. In our case the receivers are fixed and their positions are known. The accuracy of their device is about ±4 mm, and the range is 3 m. The difference with our device is that we use three receivers on the same robot so that it can perceive the relative angle between two robots.

5 Conclusion and Future Work

In this paper we present an ultrasonic device that can be used by mobile robots to position themselves relative to each other. The device, made of one ultrasonic transmitter, three ultrasonic receivers and a RF link, is omnidirectional and has an accuracy of about ±3.75 mm and ±1.84° over a range of 8.1 m. The receivers are placed on a circular surface of 100 mm radius, but other configurations are possible as long as their exact positions are known and that no objects are placed between them. The performance can be improved even more by putting the receivers as far away as possible of each other. Each device consumes about 150 mA at 7.5 Vdc, and costs about 125$US of material.

When using such devices with a group of mobile robots, the principal limiting factor is that the data rate is proportional to the number of robots in the group, since only one device can be used as a transmitter at all time. Depending on the area covered by the group, strategies can be derived to activate localization for robots that are not in the same perceptual range. In future work, we plan to improve the device by adding another receiver in order to make it determines position in 3-D instead of 2-D. For instance, if the transducers used can act both as emitter and receiver, the transmitter could be used as the fourth receiver for 3-D positionning. We also want to consider the effect of the temperature on the speed of sound, and to select transducers that would not interfere with conventional sonars used for proximity detection on robots. We will validate the improved devices using a group of robots moving in formations.

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References

[1] A. Das, R. Fierro, V. Kumar, J. Ostrowski, J. Spletzer, and C. Taylor. A framework for vision-based formation control. *IEEE Transactions on Robotics and Automation*, 2002.

[2] H. R. Everett. *Sensors for Mobile Robots.* A.K. Peters, 1995.

[3] F. Figueroa and A. Mahajan. A robust navigation system for autonomous vehicles using ultrasonics. *Control Engineering Practice*, 2(1):49–54, February 1992.

[4] F. Figueroa and A. Mahajan. A robust method to determine the coordinates of a wave source for 3-d position sensing. *Journal of Dynamic Systems, Measurement, and Control*, 116:505–511, 1994.

[5] D. Fox, W. Burgard, H. Kruppa, and S. Thrun. Collaborative multi-robot localization. In *Proc. German Conf. on Artificial Intelligence (KI), Lecture Notes in Computer Science*, volume 1701, pages 255–262, 1999.

[6] J. Freslund and M. J. Mataric. Robots in formation using local information. In *Proc. 7th Int. Conf. on Intelligent Autonomous Systems*, 2002.

[7] F. Michaud, D. Letourneau, M. Guilbert, and J.-M. Valin. Dynamic robot formations using directional visual perception. In *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, 2002.

[8] F. Michaud and M.T. Vu. Managing robot autonomy and interactivity using motives and visual communication. In *Proc. Int. Conf. on Autonomous Agents*, pages 160–167, May 1999.

[9] L. E. Navaro-Serment, C. J. J. Paredis, and P. K. Khosla. A beacon system for the localization of distributed robotic teams. In *Proc. Int. Conf. on Field and Service Robotics*, 1999.

[10] C.-J. Wu and C.-C. Tsai. Localization of an autonomous mobile robot based on ultrasonic sensory information. *Journal of Intelligent and Robotic Systems*, 30:267–277, 2001.